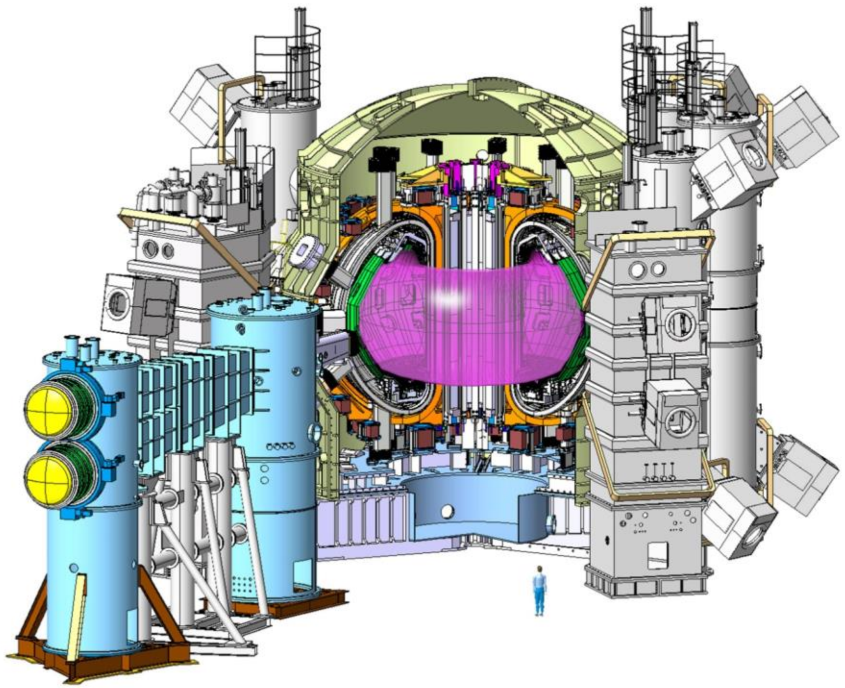
DEVELOPMENT OF EQUILIBRIUM CONTROL SIMULATOR AND EXPERIMENTAL VALIDATION OF ADVANCED ISO-FLUX EQUILIBRIUM CONTROL DURING THE FIRST OPERATIONAL PHASE OF JT-60SA

S. Inoue, Y. Miyata, S. Kojima, T. Wakatsuki, M. Takechi, Y. Ohtani,
Y. Ko, M. Yoshida, H. Urano, and T. Suzuki

QST National Institutes for Quantum Science and Technology

JT-60SA Advanced Superconducting Tokamak
BA-Satellite Tokamak Program

JT-60SA project



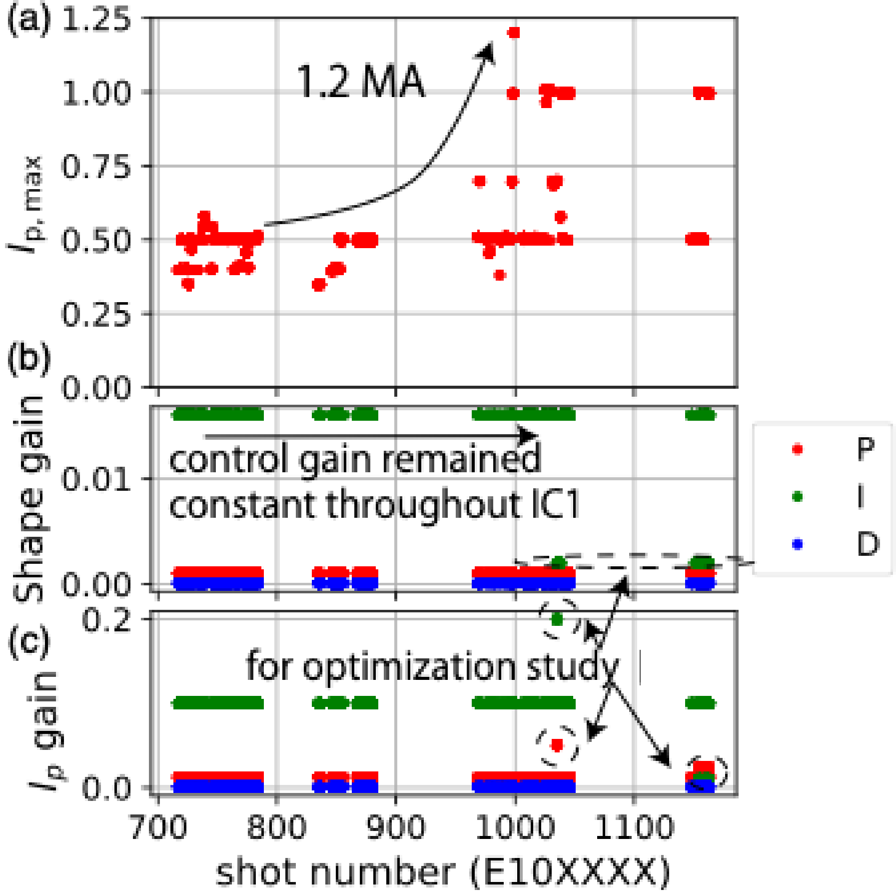
- Joint international fusion experimental device being built and operated by Japan and Europe, in Naka, Japan
- Main characteristics:
  - Large (~3.0 m major radius) superconducting devise
  - High power (41 MW) and long pulse (~100 s) capability
- Target plasma parameters:
  - High current (5.5 MA) and highly shaped ($\kappa_X \sim 1.9$, $\delta_X \sim 0.5$) plasmas with long sustainment (~100 s)

Address key scientific and technological issues for ITER and DEMO

⇩

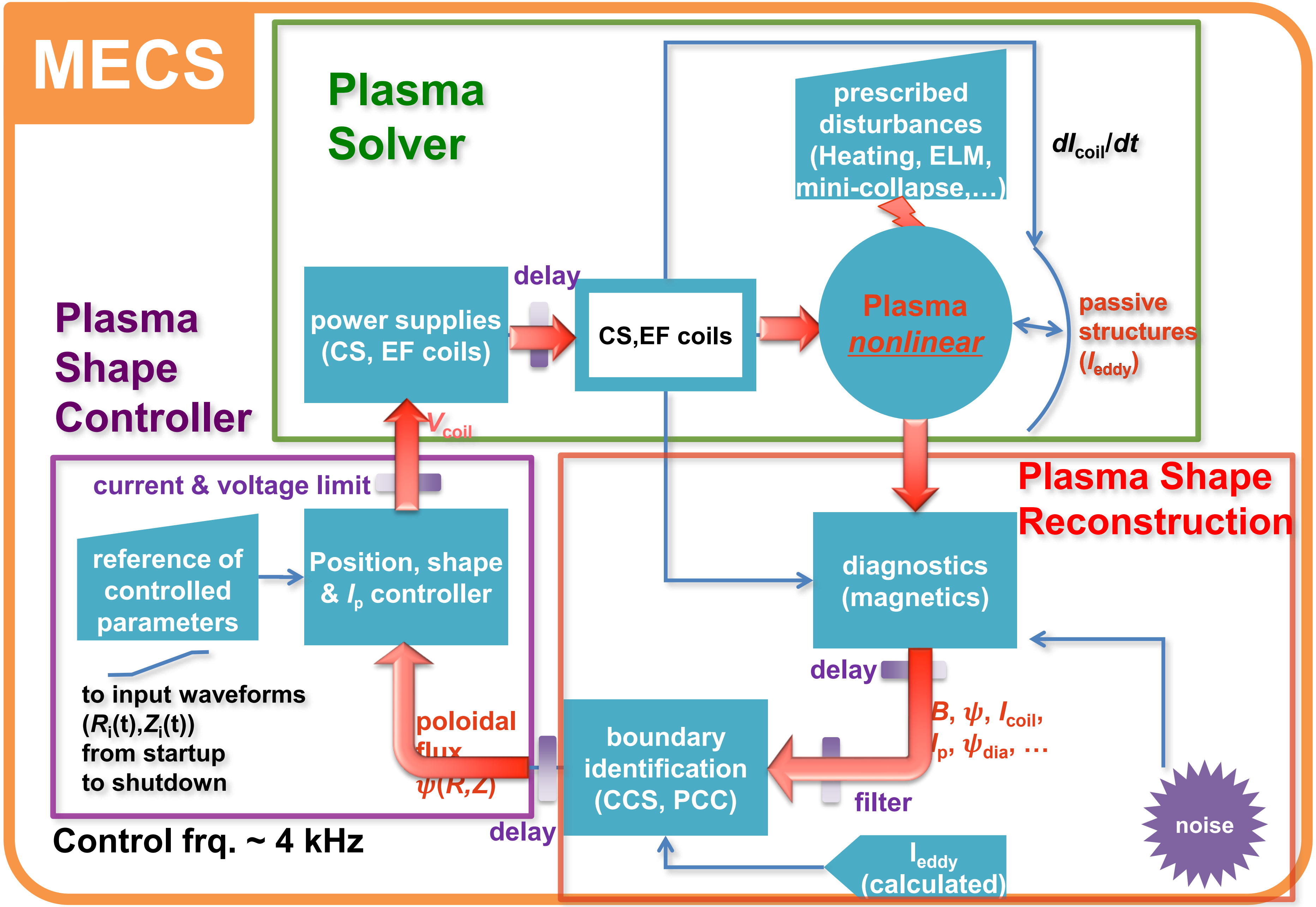
Equilibrium control is essential

Pre-studied control gain worked without any modification



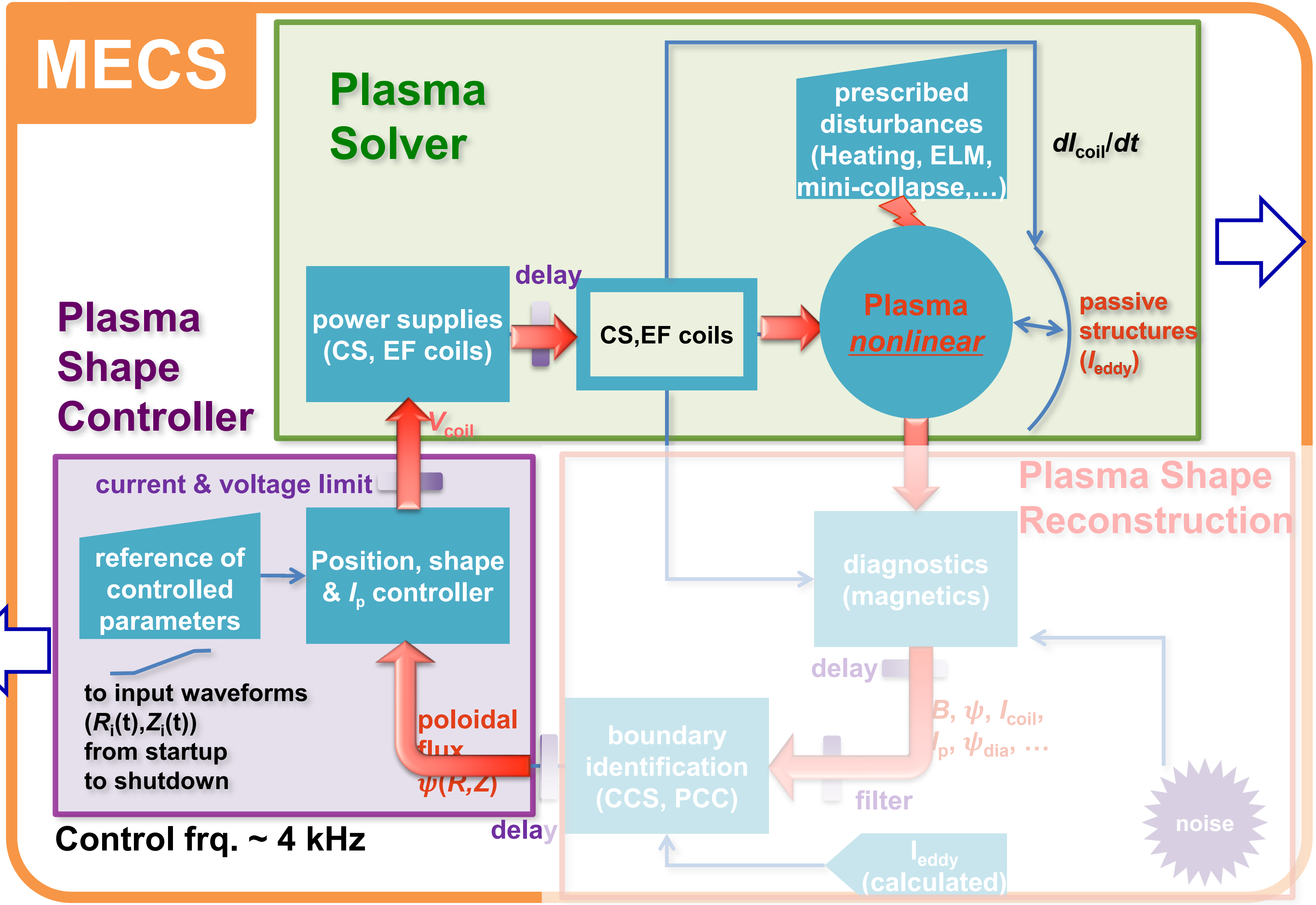
- In the first operation (integrated commissioning, IC) in 2023, ~200 shots with plasma were performed
  - 1.2 MA diverted plasma
  - Pre-studied control gains by simulator, MECS, worked **without any modification**
- Key question*: **Why did the predictions work so well?***
- **Objective: to reveal the essential physics required for accurate prediction of equilibrium control → directly linked to fusion performance**
- **Achievement: first identification of the nonlinear response/axisymmetric field amplification of plasma**

Overview of MECS: plasma simulator with realistic experimental conditions, limits, and disturbances (noise, delay, …) of JT-60SA



[1] Y. MIYATA, T. SUZUKI, T. FUJITA, S. IDE, and H. URANO, "Development of a Simulator for Plasma Position and Shape Control in JT-60SA," Plasma Fusion Res **7**(0), 1405137–1405137 (2012).

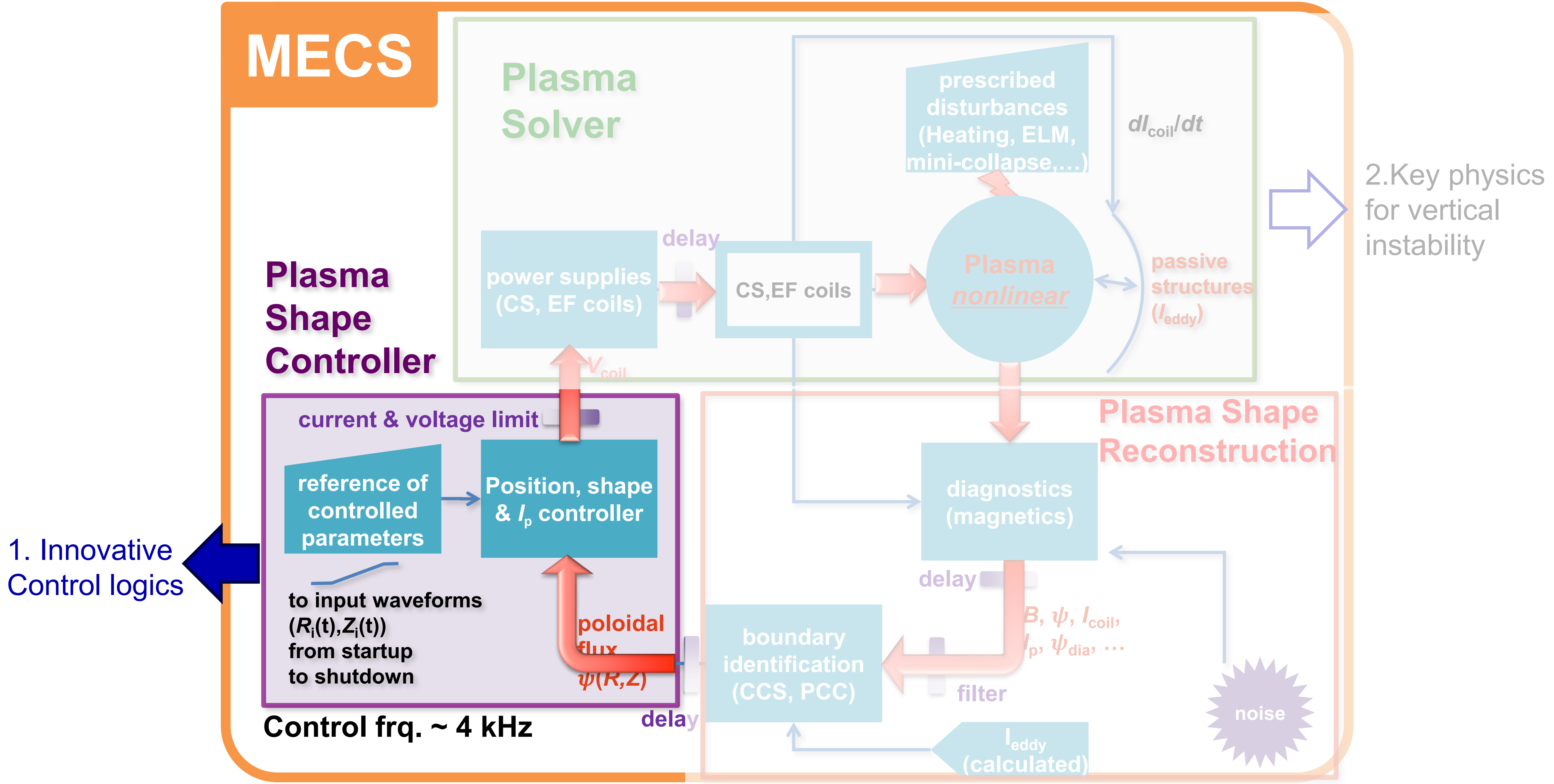
Overview of MECS: plasma simulator with realistic experimental conditions, limits, and disturbances (noise, delay, …) of JT-60SA



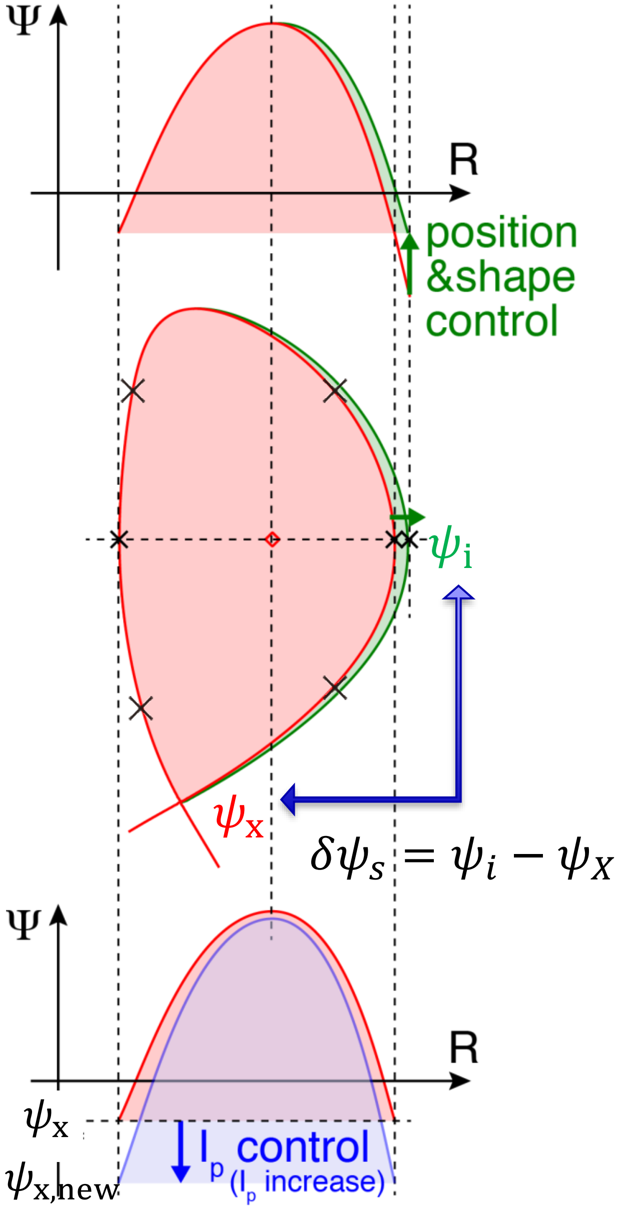
1. Innovative Control logics

2.Key physics for vertical instability

Overview of MECS: plasma simulator with realistic experimental conditions, limits, and disturbances (noise, delay, …) of JT-60SA



Control Model and adaptive voltage allocation scheme



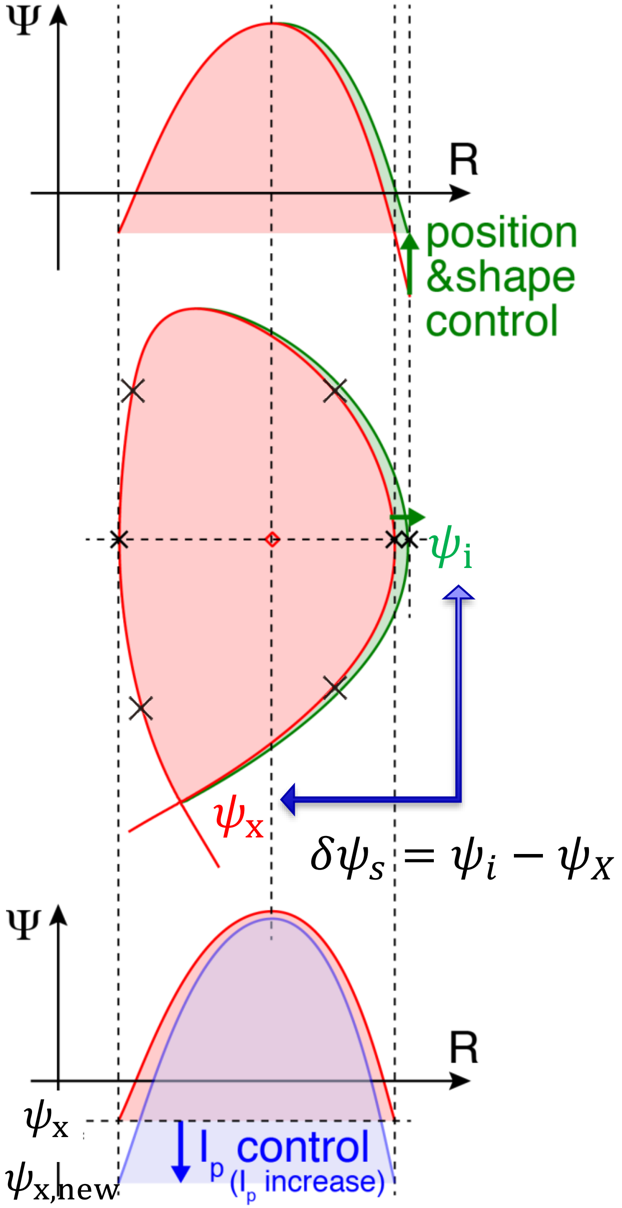
ISO-FLUX control

(Shape) $\delta\boldsymbol{\psi}_S$: X-point and prescribed control points

(Ip) $\delta\boldsymbol{\psi}_X$: Offset of all control points

$$\delta\boldsymbol{\psi} = \delta\boldsymbol{\psi}_S + \delta\psi_X$$

Control Model and adaptive voltage allocation scheme



ISO-FLUX control

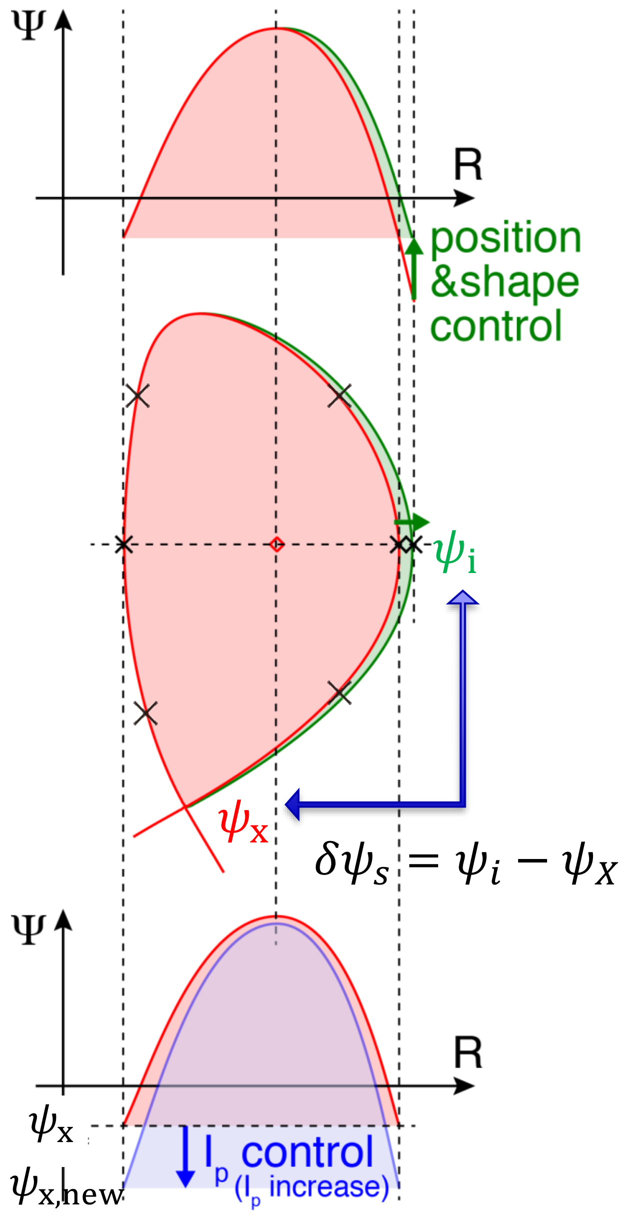
(**Shape**) $\delta\boldsymbol{\psi}_S$: X-point and prescribed control points

(**Ip**) $\delta\boldsymbol{\psi}_X$: Offset of all control points

$$\delta\boldsymbol{\psi} = \delta\boldsymbol{\psi}_S + \delta\psi_X$$

Control eq. $f_1(\delta\boldsymbol{\psi}) = \delta\boldsymbol{I}_c$ ← required change of coil current

Control Model and adaptive voltage allocation scheme



ISO-FLUX control

(**Shape**) $\delta\boldsymbol{\psi}_S$: X-point and prescribed control points

(**Ip**) $\delta\boldsymbol{\psi}_X$: Offset of all control points

$$\delta\boldsymbol{\psi} = \delta\boldsymbol{\psi}_S + \delta\psi_X$$

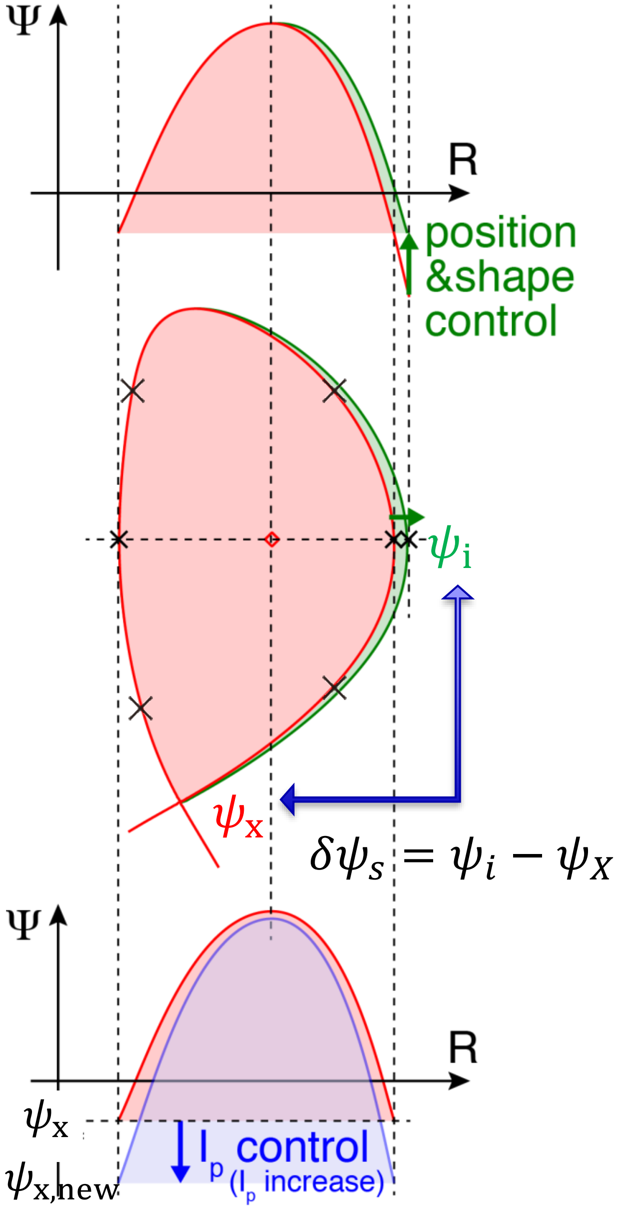
⇩

Control eq. $f_1(\delta\boldsymbol{\psi}) = \delta\boldsymbol{I}_c$ ← required change of coil current

⇩

Circuit eq. $f_2(\delta\boldsymbol{I}_c) = \boldsymbol{V}_c$ ← voltage command

Control Model and adaptive voltage allocation scheme



ISO-FLUX control

(Shape) $\delta\boldsymbol{\psi}_{\mathrm{S}}$: X-point and prescribed control points

(Ip) $\delta\boldsymbol{\psi}_{\mathrm{X}}$: Offset of all control points

$$\delta\boldsymbol{\psi} = \delta\boldsymbol{\psi}_{\mathrm{S}} + \delta\psi_{\mathrm{X}}$$

Control eq. $f_1(\delta\boldsymbol{\psi}) = \delta\boldsymbol{I}_{\mathrm{c}}$ ← required change of coil current

Circuit eq. $f_2(\delta\boldsymbol{I}_c) = \boldsymbol{V}_{\mathrm{c}}$ ← voltage command

Adaptive voltage allocation scheme

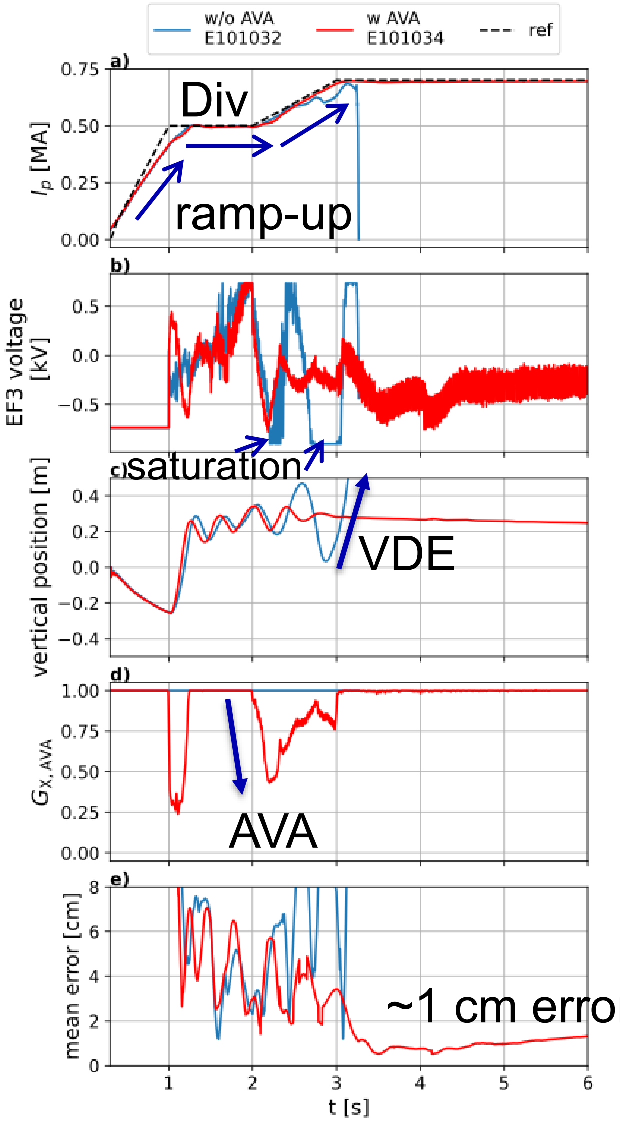
Inoue+, NF21, 23

$$\boldsymbol{G}_{\mathrm{X,AVA}} \equiv \frac{|(f_1 f_2)^{-1}(\boldsymbol{V}_{\mathrm{c,lim}})|}{|\delta\psi_{\mathrm{X}}|}$$

⇦ **Magnetic flux controllable under rated voltage limits**

$$\delta\boldsymbol{\psi}_{\mathbf{for\ control}} = \delta\boldsymbol{\psi}_{\mathrm{S}} + \boldsymbol{G}_{\mathrm{X,AVA}}\delta\psi_{\mathrm{X}}$$

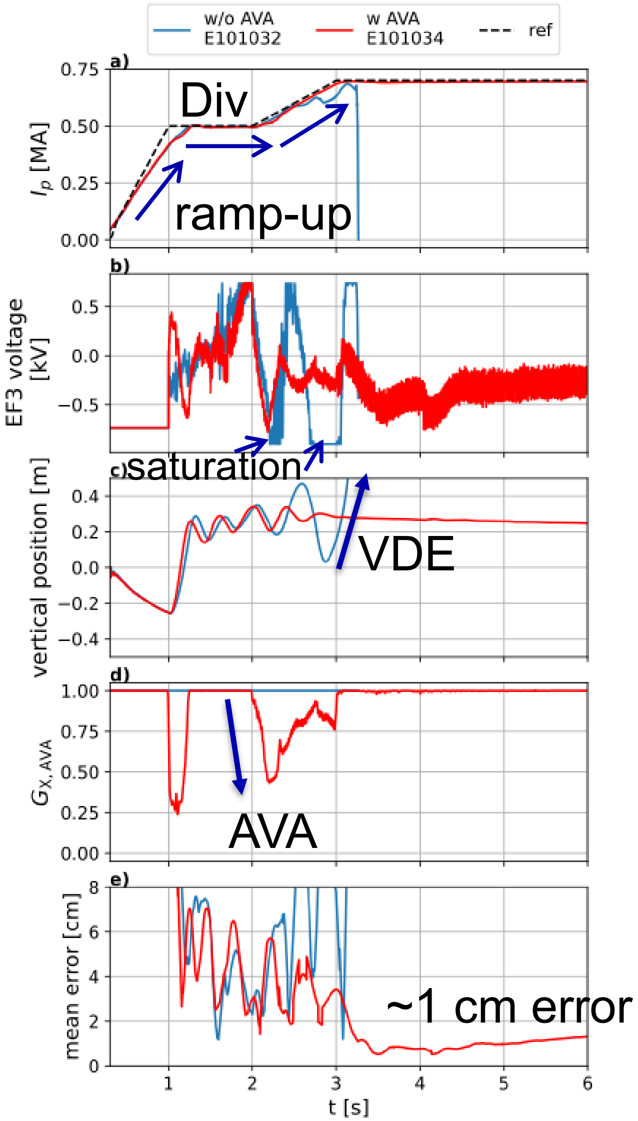
AVA scheme resolved Ip/PS interference in IC



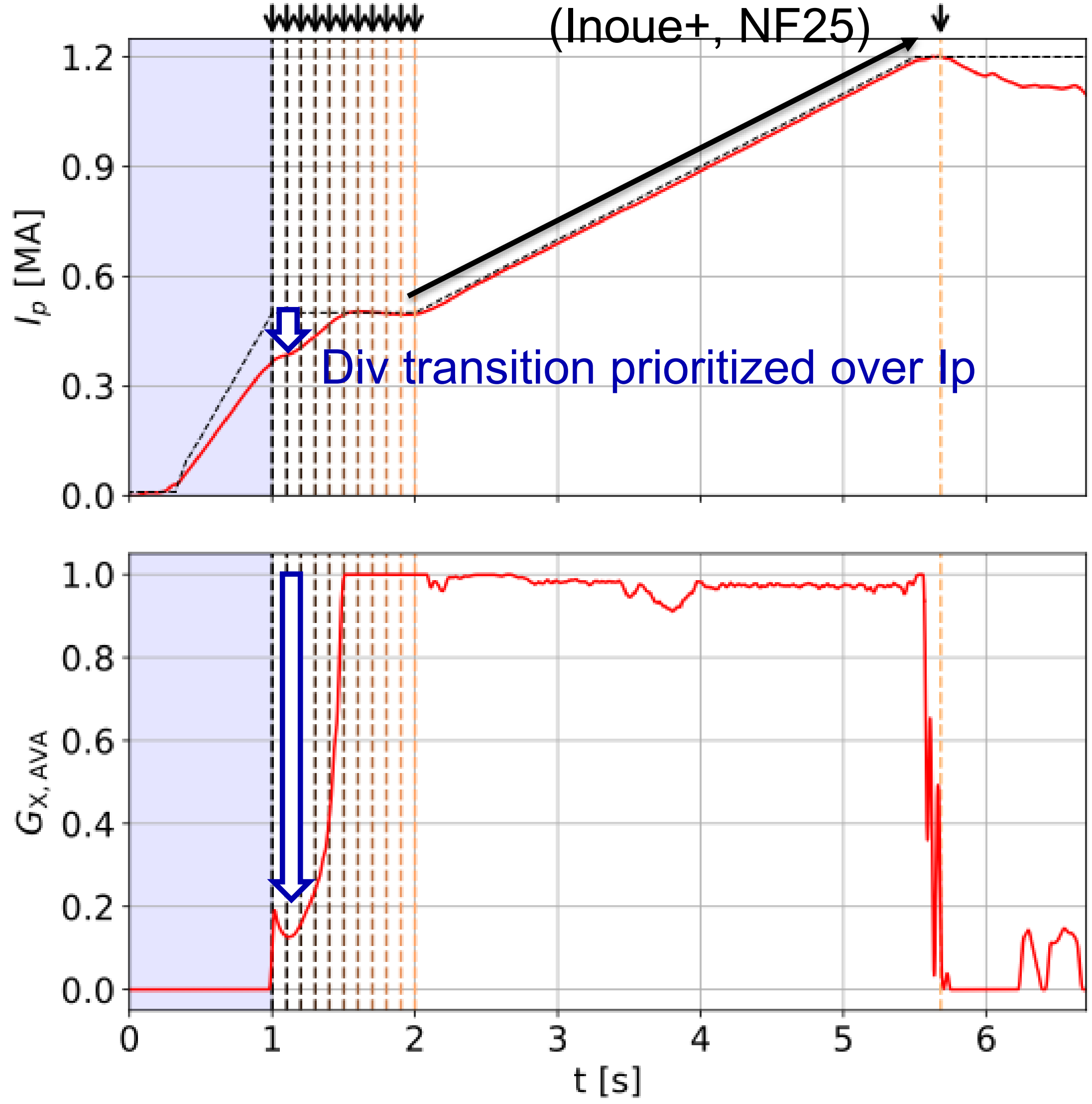
- Discharge: ramp-up to 500 kA → transition to divertor configuration → ramp-up to 750 kA
- Without AVA: oscillations during ramp-up and transition, leading to VDE
- With AVA: $G_{\mathrm{X,AVA}}$ resolved the voltage saturation and oscillations were suppressed, leading successful operation
  - Mean error < 2 cm

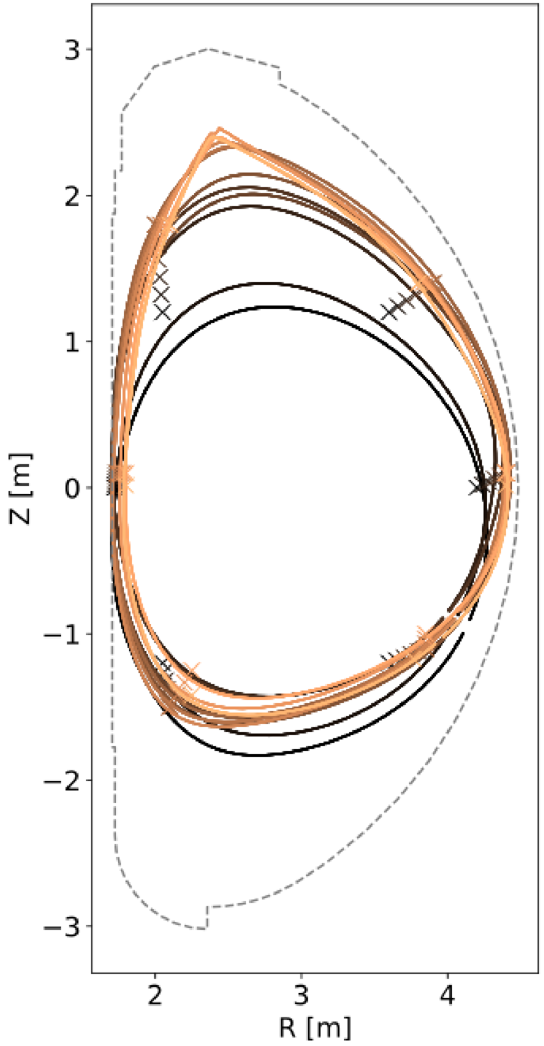
~1 cm error (LCFS ⬄ Reference points)

Diverted 1.2 MA plasma was achieved

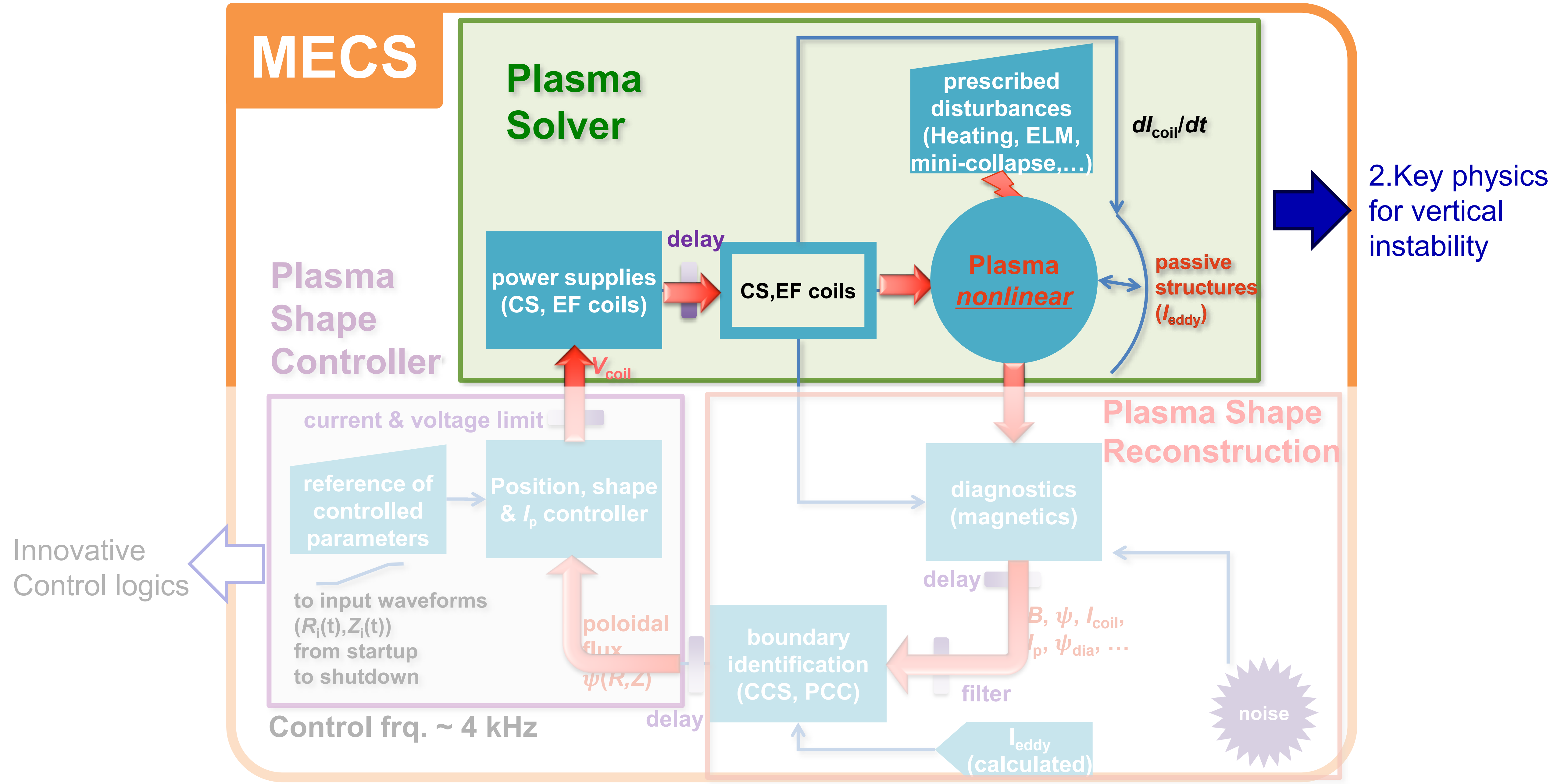


1.2 MA achieved!, largest Ip as SC tokamak (Inoue+, NF25)

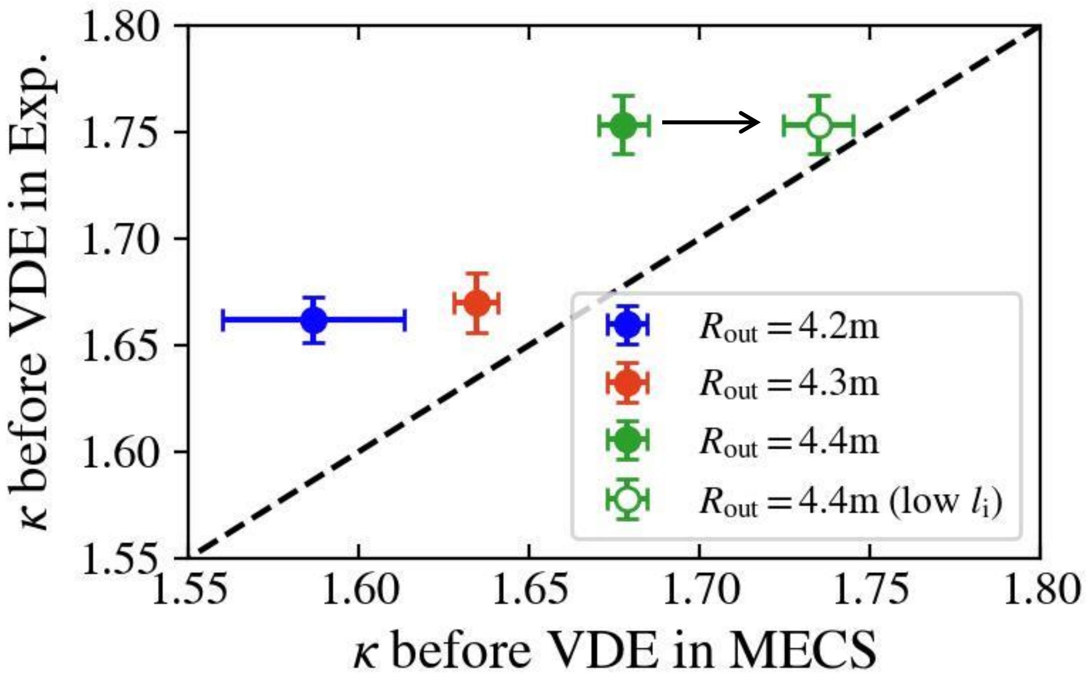




Overview of MECS: plasma simulator with realistic experimental conditions, limits, and disturbances (noise, delay, …) of JT-60SA



Physics background of MECS



Yokoyama+, P5-2690

- From the energy principle, vertical instability (VI) appears as a minimum of plasma energy and wall/coil magnetic energy
  - Energy of plasma is proven to be perturbed Grad-Shafranov eq.[1]
- MECS, CREATE-NL, or DINA code can self-consistently simulate VI by coupling circuits equations with free-boundary Grad–Shafranov eq.
- MECS simulation captures the lower limit of accessible κ — JT-60SA experiments went beyond it

Is self-consistent (but time-consuming) VI calculation indispensable for simulator?

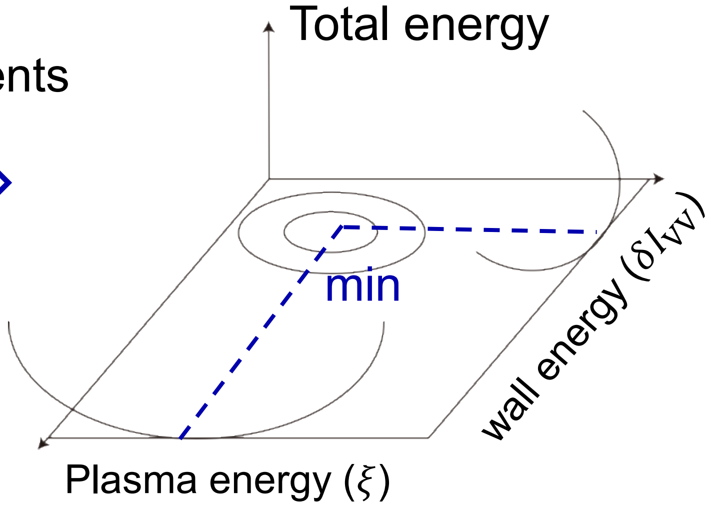
[1] J.P. Freidberg, A. Cerfon, and J.P. Lee, “Tokamak elongation – how much is too much? Part 1. Theory,” J Plasma Phys **81**(6), 515810607 (2015).

Open loop response experiments for comparison between Linear and Nonlinear model

- Nonlinear Model (MECS)

Change of coil currents

$\delta \boldsymbol{I}_c$ ⇨



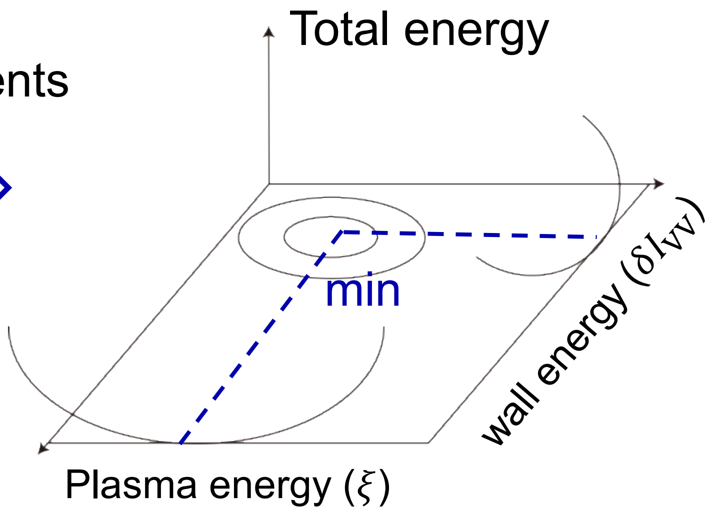
⇨ $\delta z_{\mathrm{plasma}}$

Open loop response experiments for comparison between Linear and Nonlinear model

- Nonlinear Model (MECS)

Change of coil currents

$\delta \boldsymbol{I}_c$ ⇨



⇨ $\delta z_{\mathrm{plasma}}$

- Linear Model

$\delta \boldsymbol{I}_c$ × $\boldsymbol{M}$ $\left\{ \begin{array}{l} \text{Rigid[1]} \\ \underline{\text{Non-rigid}}\text{[2]} \end{array} \right.$ ⇨ $\delta z_{\mathrm{plasma}}$

⇩

Pre-calculated from coil variation–equilibrium relation

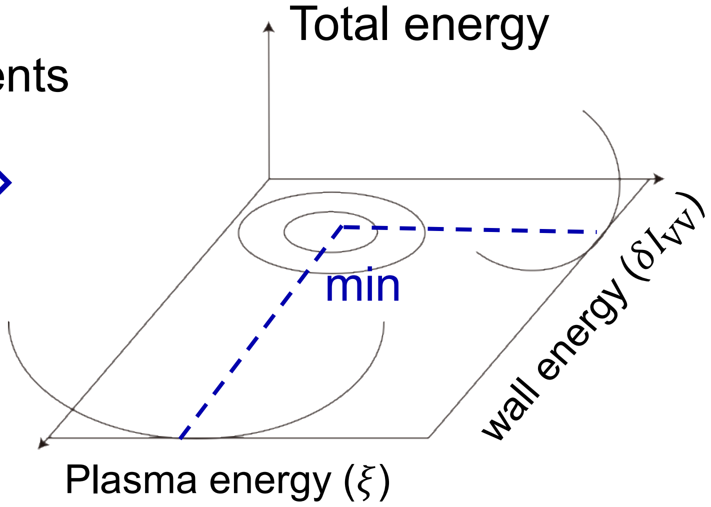
[1] A. Coutlis, *et al.*, Nucl Fusion **39**(5), 663–683 (1999).
[2] A. Portone, Nucl. Fusion **45**(8), 926–932 (2005).

Open loop response experiments for comparison between Linear and Nonlinear model

- Nonlinear Model (MECS)

Change of coil currents

$\delta \boldsymbol{I}_c \Rightarrow$



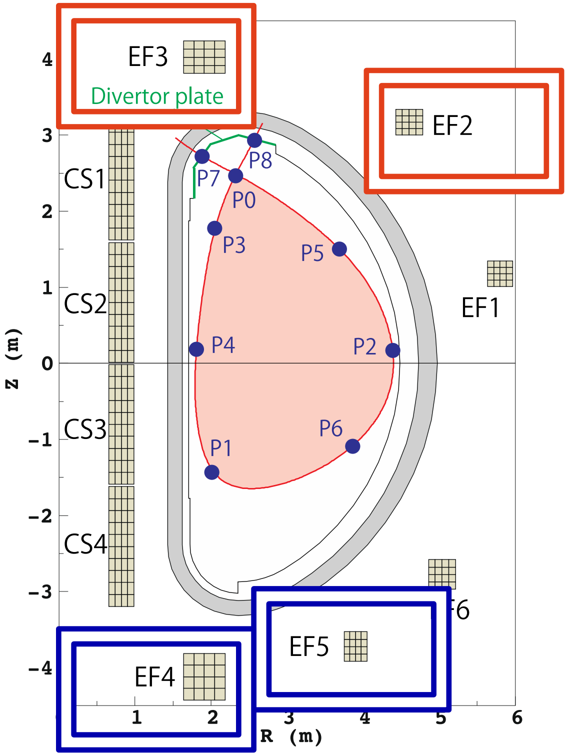
$\Rightarrow \delta z_{\rm plasma}$

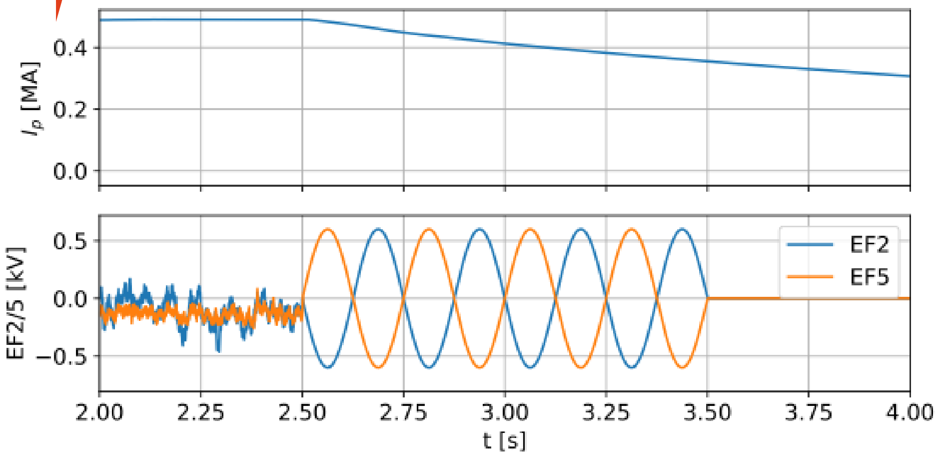
- Linear Model

$\delta \boldsymbol{I}_c \times \boldsymbol{M} \begin{cases} \text{Rigid[1]} \\ \underline{\text{Non-rigid[2]}} \end{cases} \Rightarrow \delta z_{\rm plasma}$

Pre-calculated from coil variation–equilibrium relation

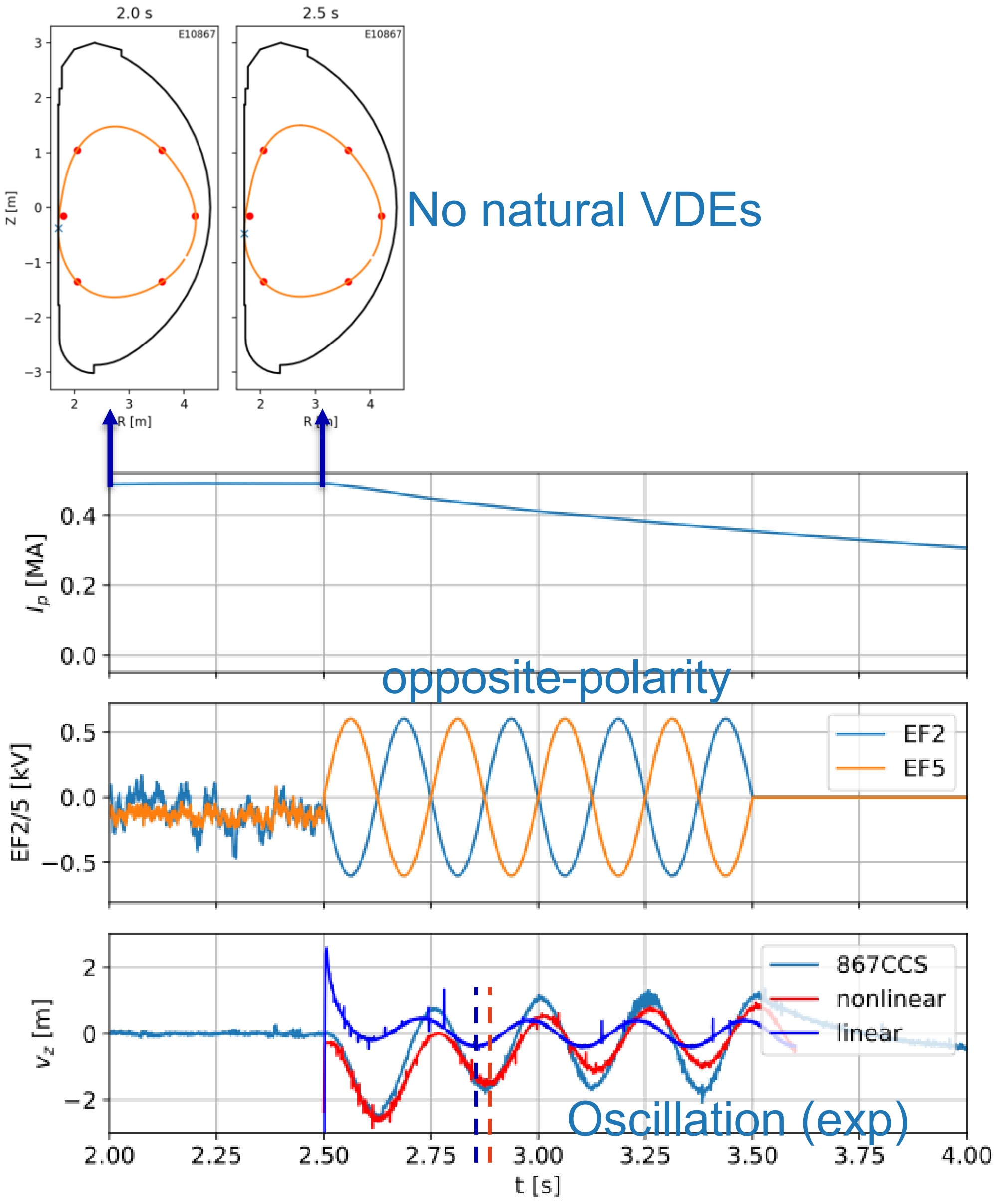
exp. validation





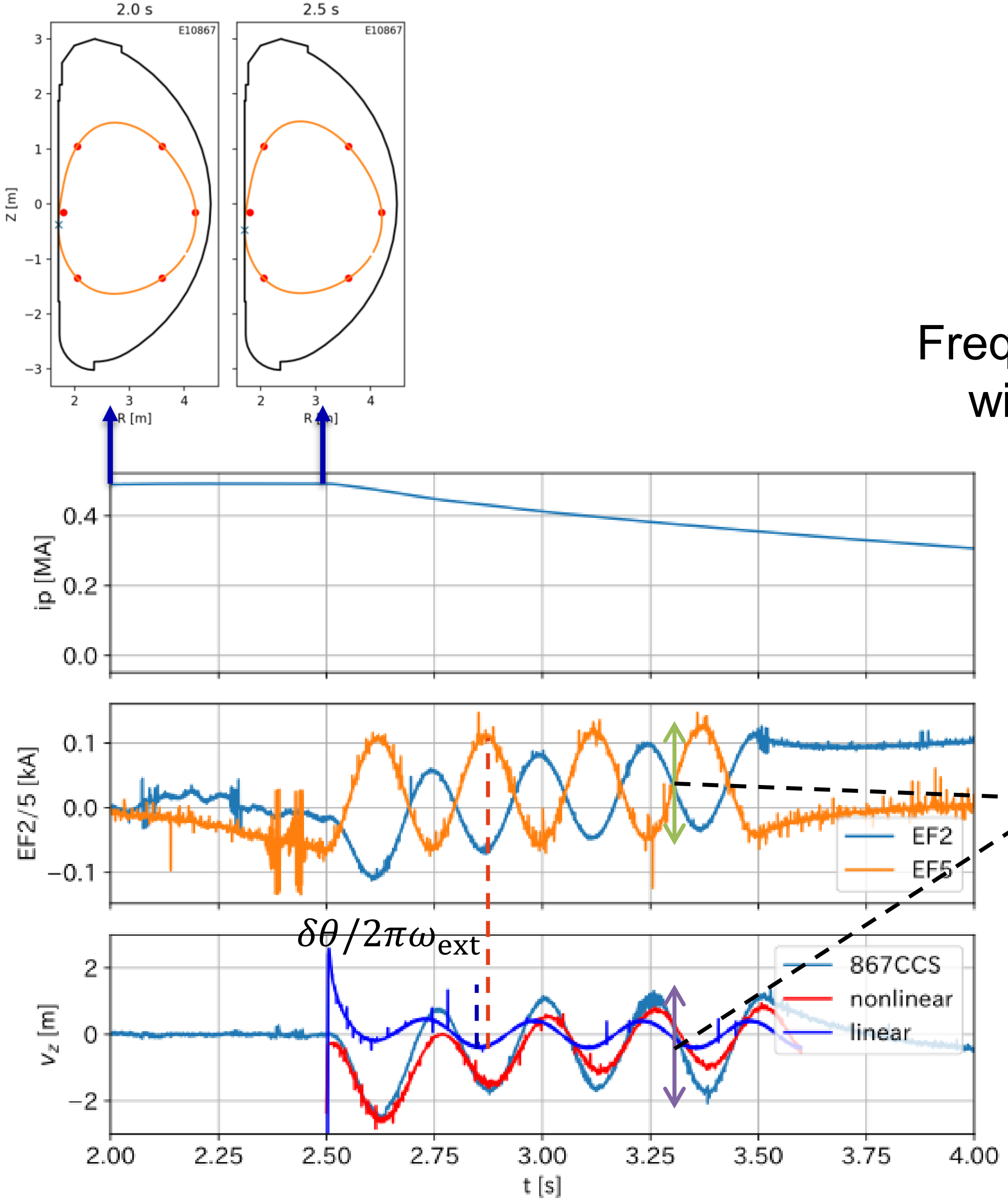
[1] A. Coutlis, *et al.*, Nucl Fusion **39**(5), 663–683 (1999).
[2] A. Portone, Nucl. Fusion **45**(8), 926–932 (2005).

Nonlinear model reproduces both amplitude and phase



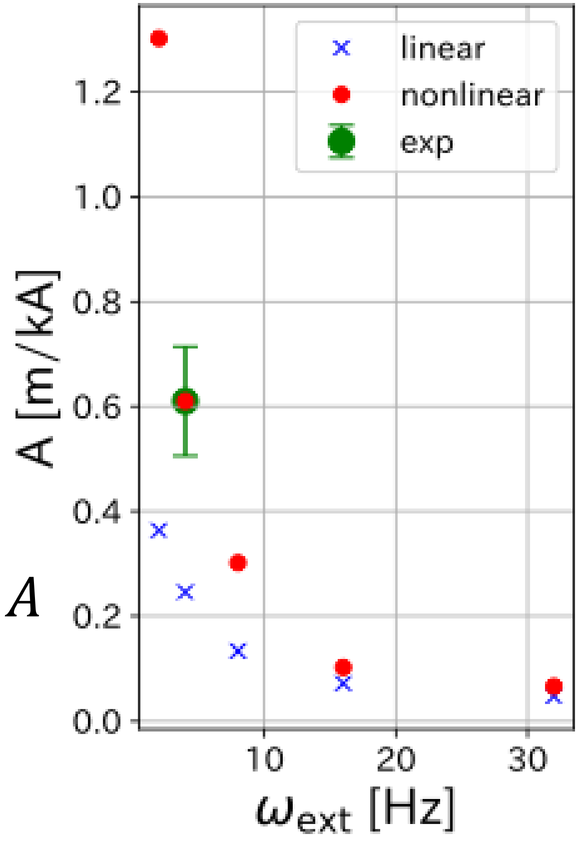
- Vertical oscillations were excited in response to change of EF coil current
- Simulations mimicking the experiment compared linear and nonlinear models
- Nonlinear model reproduced both amplitude and phase of the experiment well

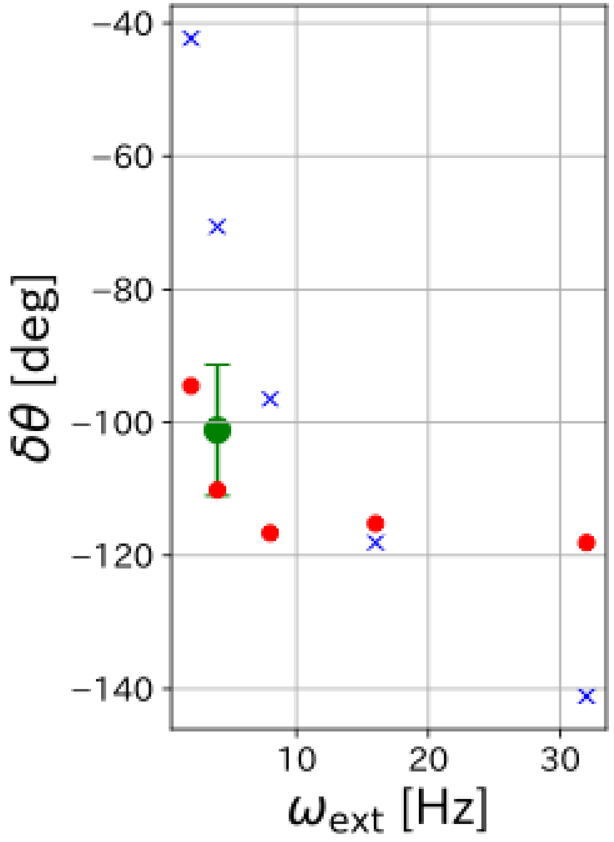
Nonlinear model reproduces both amplitude and phase



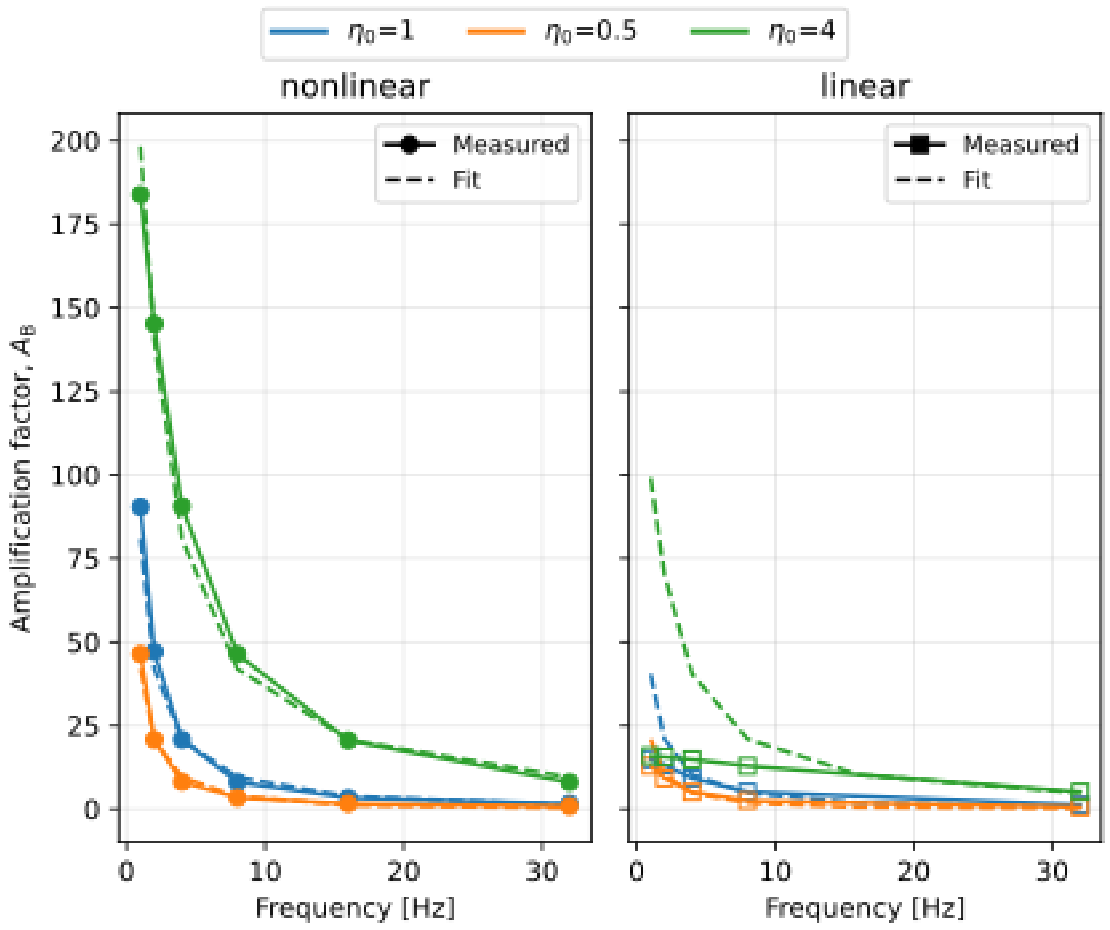
Frequency scan with MECS

$$\frac{\delta z}{\delta I_c} = A$$





Proposed RFA model qualitatively reproduces the nonlinear response



- Strong amplification at low frequency range is consistent with **Resonant Field Amplification (RFA)** of the stable n=0 resistive wall mode
- In simulations, wall resistivity was scanned from x1/2 to x4 to examine the response
- Following the RFA formulation[1]:

$$\tau_W \frac{dB_s}{dt} = \gamma_0 \tau_W B_s + M^* B_{\mathrm{ext}}$$

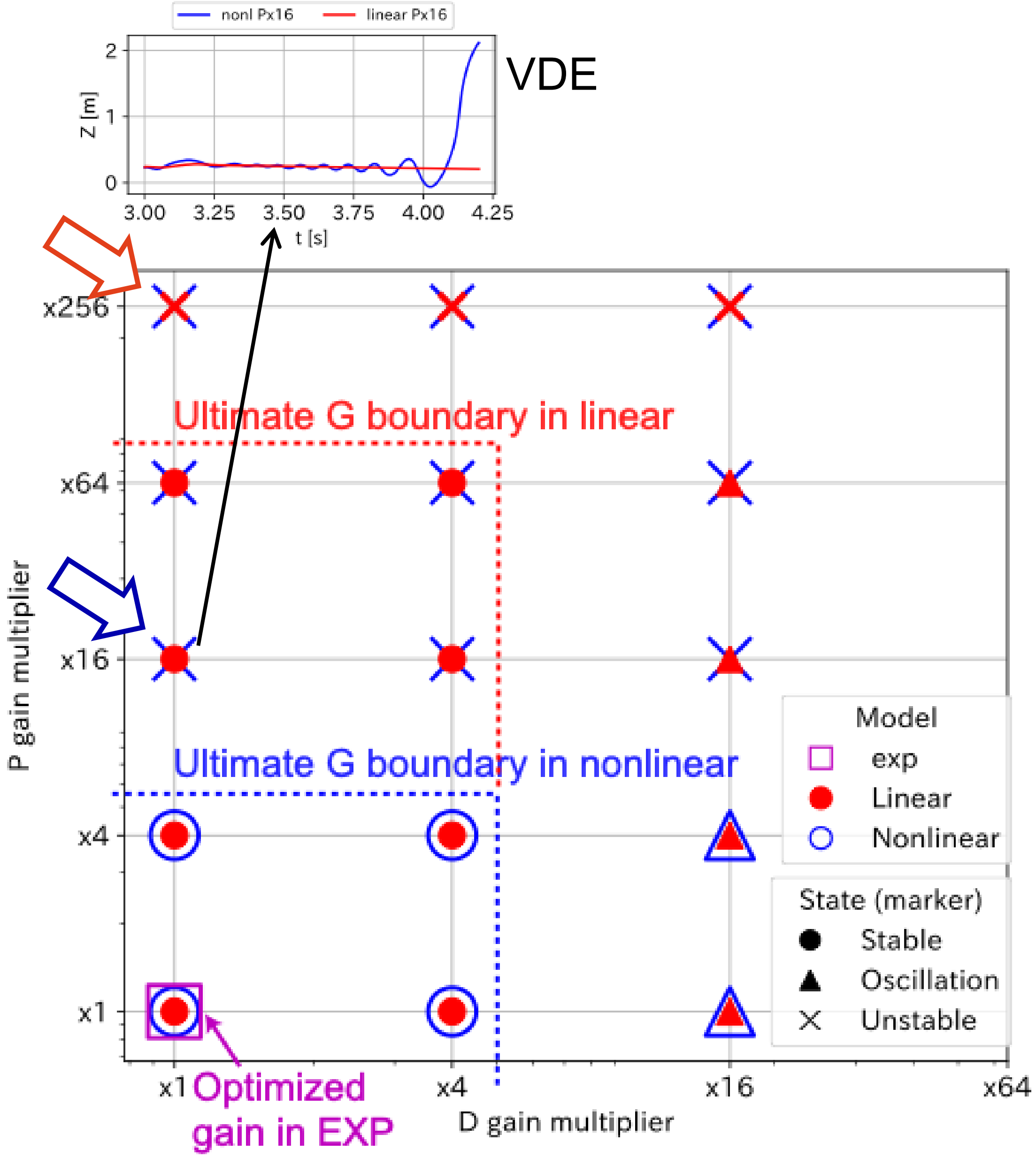
- Including eddy-current shielding in B_{ext} and assuming $\delta z_s \sim B_s$,the transfer gives:

$$\frac{\delta z_s}{B_{\mathrm{ext}}} \exp \delta\theta = \frac{A_0}{(1 + i\omega\tau_W)(i\omega\tau_W - \gamma_0)}$$

- This model qualitatively **reproduces the response** with $\tau_W = 450$ ms, and $\gamma_0 = -20.7$ s^{-1}

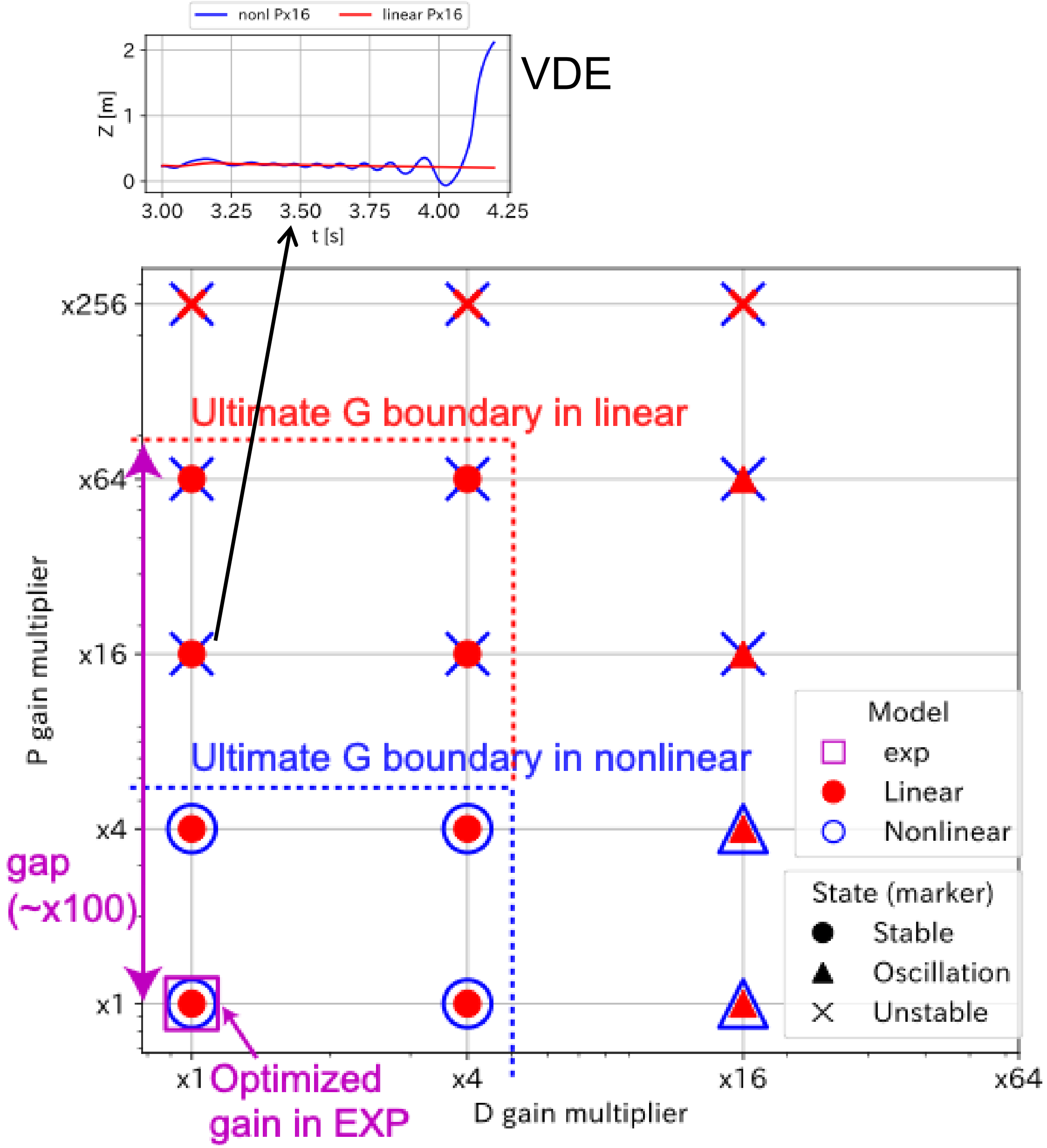
[1] A.M. Garofalo, et al., "Sustained Stabilization of the Resistive-Wall Mode by Plasma Rotation in the DIII-D Tokamak," Phys Rev Lett **89**(23), 235001 (2002).

Closed-Loop Response: Importance of Nonlinearity



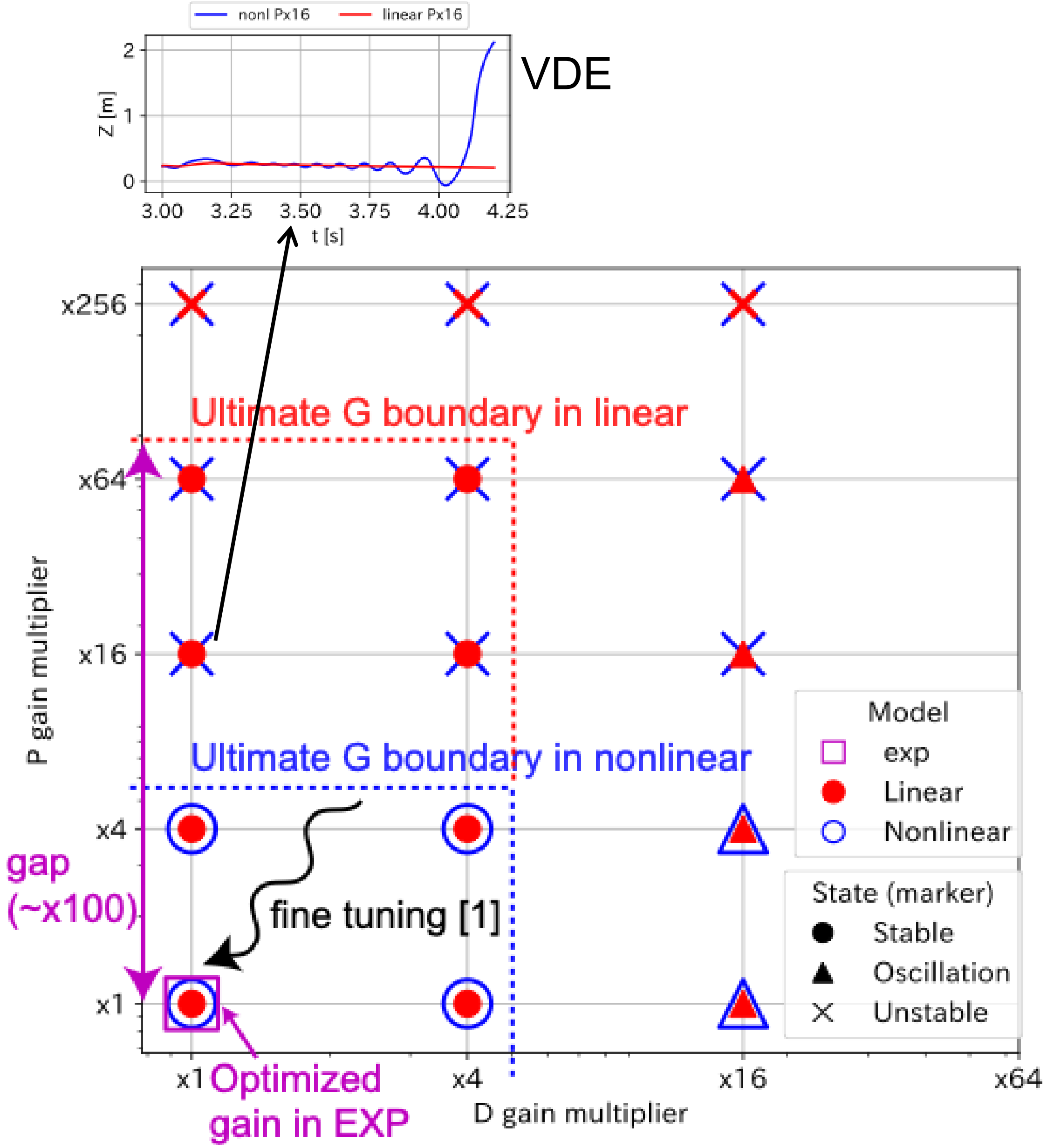
- Feedback control is applied in both models
- Optimized gain in exp. is unity
- Ultimate sensitivity gains are calculated by changing the PD gain
- Linear (red): unstable at ×256; Nonlinear (blue): unstable already at ×16

Closed-Loop Response: Importance of Nonlinearity



- Feedback control is applied in both models
- Optimized gain in exp. is unity
- Ultimate sensitivity gains are calculated by changing the PD gain
- Linear (red): unstable at ×256; Nonlinear (blue): unstable already at ×16
- Linear model: Ultimate sensitivity gains ≈ x100 higher → significant gap from the experiment

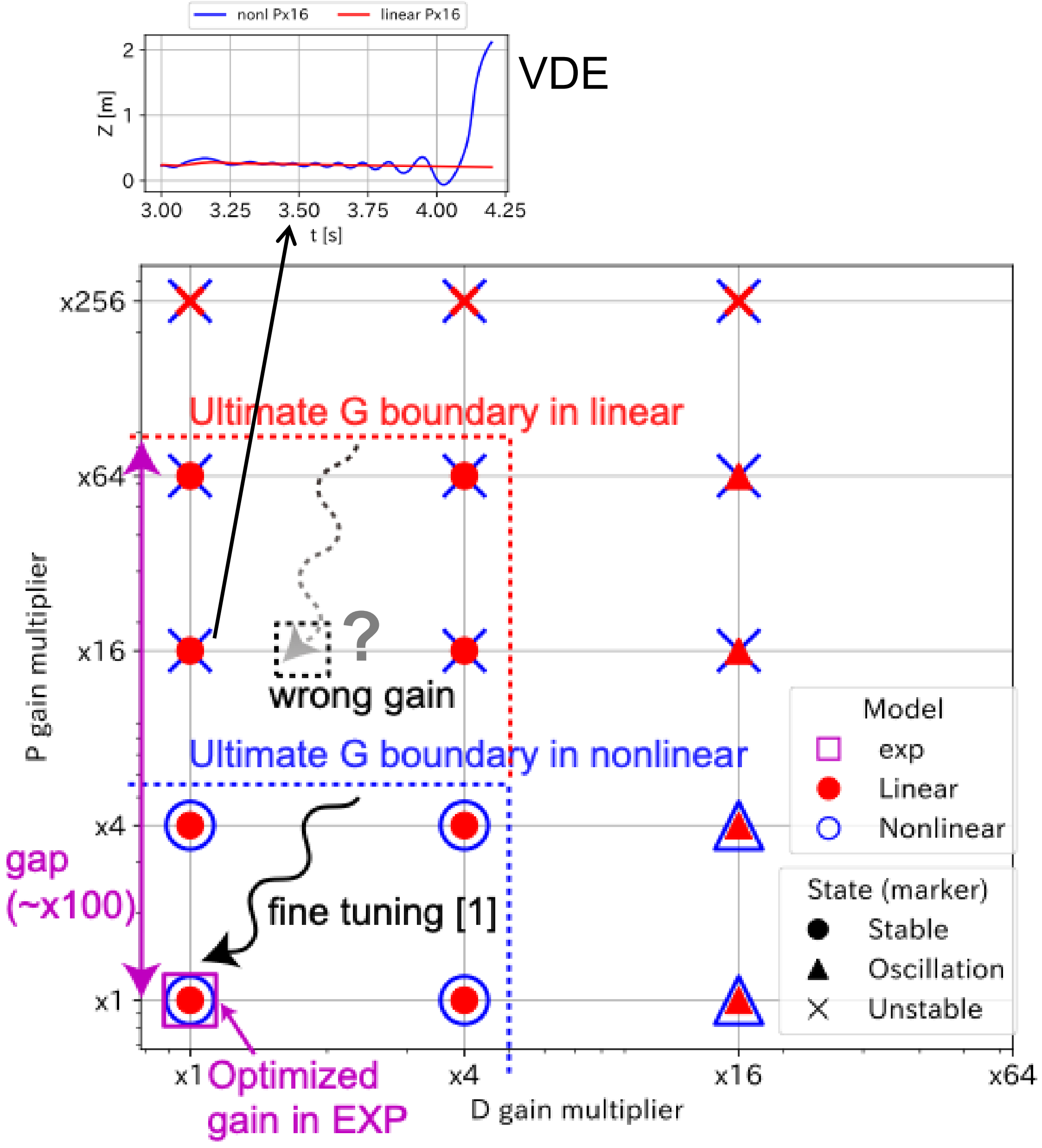
Closed-Loop Response: Importance of Nonlinearity



- Feedback control is applied in both models
- Optimized gain in exp. is unity
- Ultimate sensitivity gains are calculated by changing the PD gain
- Linear (red): unstable at ×256; Nonlinear (blue): unstable already at ×16
- Linear model: Ultimate sensitivity gains ≈ x100 higher → significant gap from the experiment
- Nonlinear model: Optimized ultimate sensitivity gains ≈ x4 experimental P, D gains
  - Optimal gain is the same order of the ultimate sensitivity gain → obtained by fine-tuning via frequency response with MECS [1]

[1] Kojima+, Nuclear Fusion 2025

Closed-Loop Response: Importance of Nonlinearity

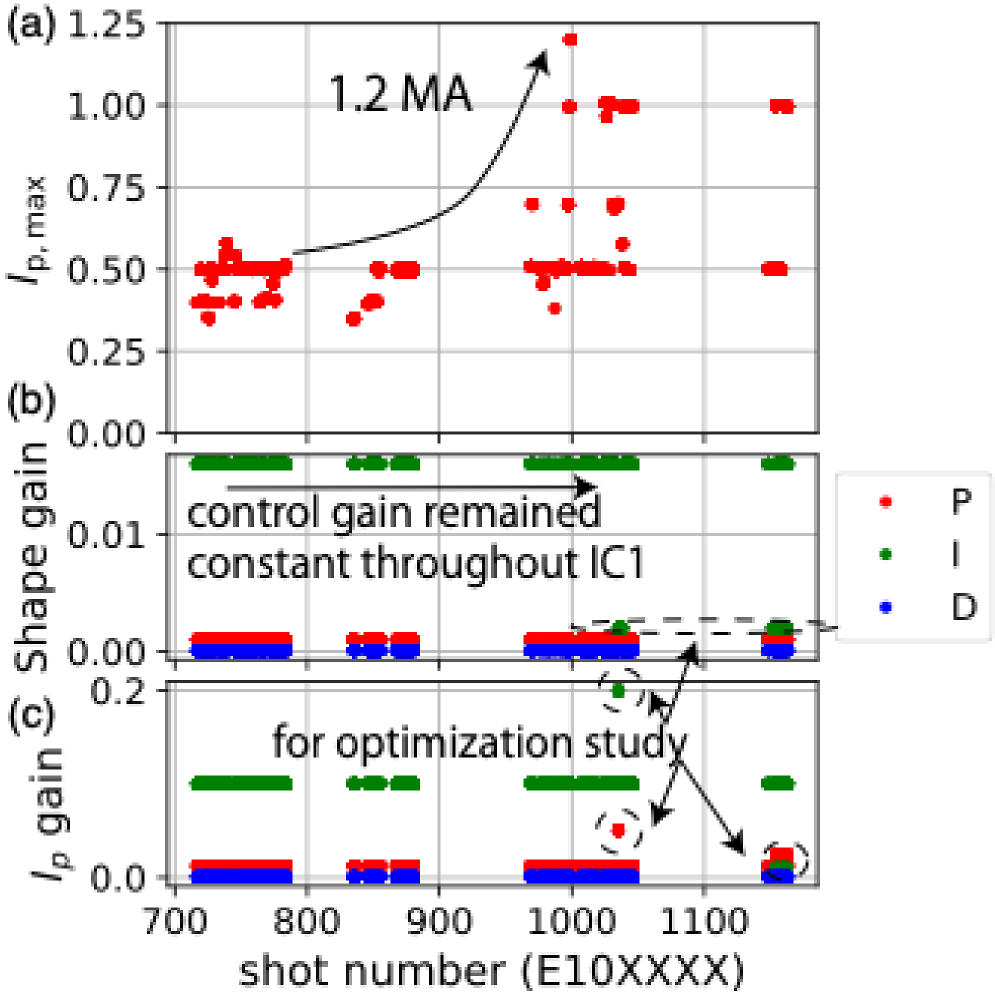


- Feedback control is applied in both models
- Optimized gain in exp. is unity
- Ultimate sensitivity gains are calculated by changing the PD gain
- Linear (red): unstable at ×256; Nonlinear (blue): unstable already at ×16
- Linear model: Ultimate sensitivity gains ≈ x100 higher → significant gap from the experiment
- Nonlinear model: Optimized ultimate sensitivity gains ≈ x4 experimental P, D gains
  - Optimal gain is the same order of the ultimate sensitivity gain → obtained by fine-tuning via frequency response with MECS [1]

➢ **Under RFA, nonlinear model is essential**

[1] Kojima+, Nuclear Fusion 2025

Summary and Future plan



- JT-60SA's first operation achieved a smooth divertor transition, 1.2 MA plasma current, and a Guinness-certified 160 m³ plasma volume, all using <u>pre-studied gains by MECS without modification</u>
  - MECS simulation captures the lower limit of accessible κ (Yokoyama+, P5-2690)

Key question: Why did the predictions work so well?

- <u>Axisymmetric resonant field amplification</u> — a key physical process governing vertical instability — <u>was self-consistently solved in MECS, enabling pre-optimization of control gains</u>
- Toward OP2, direct control logic for κ & δ, together with the use of in-vessel coils & stabilization plates, will enable operation with **κ > 2** (Kojima+, P6-2716)

backup

Nonlinear model

Loop 1 Plasma current update:

$I_p^n \rightarrow I_p^{n+1}$ by Poynting's theorem and using external inductance as

$$\frac{\partial}{\partial t}\left(\underbrace{L_p}_{\text{Plasma inductance}} I_p + \underbrace{\alpha C_E \mu_0 R_0 I_p) + \dot{\psi}_{\text{res}}}_{\text{Resistive flux consumption}} + \underbrace{\frac{\partial}{\partial t}\left(\sum_{\text{coil}} M_{\text{cp}} I_c + \sum_{\text{vv}} M_{\text{vp}} I_v\right)}_{\text{coil\&vv mutual inductance}} = 0$$

Loop 2

- Magnetic axis update: $\boldsymbol{x}_{\text{ax}}^n \rightarrow \boldsymbol{x}_{\text{ax}}^{n+1}$
- Imaginary quadrupole field update: $\boldsymbol{B}_i^n \rightarrow \boldsymbol{B}_i^{n+1}$ with $B_r(\boldsymbol{x}_{\text{ax}}^{n+1}) = B_z\ (\boldsymbol{x}_{\text{ax}}^{n+1}) = 0$
- Poloidal flux convergence: $\psi_p^n \rightarrow \psi_p^{n+1}$ by $-\Delta\psi = FF' + p'$
- Eddy currents update: $I_v^n \rightarrow I_v^{n+1}$ by $\underbrace{M_{\text{vv}} \frac{\partial I_v}{\partial t} + M_{\text{cv}} \frac{\partial I_c}{\partial t} + \frac{\partial (M_{\text{pv}} I_p)}{\partial t}}_{\text{vv, coil, and plasma mutual inductances}} + \underbrace{R I_v}_{\text{VV resistance}} = 0$
- Plasma current profile update: $j_p^n(\psi) \rightarrow j_p^{n+1}(\psi)$ for $\beta_p \& l_i$ convergence to prescribed values

Loop 2 converged?

Loop 1 converged?

Linear Model

- Implemented following the non-rigid model [1]

$$L^*\dot{x} + Rx = V,$$

Current center vertical displacement → $z_p = Cx,$ (1)

where x is the vector of length N_c of mesh currents [8] and V the vector of voltages applied to the active coils. The elements of the $N_c \times N_c$ modified inductance matrix L^* [2] and $1 \times N_c$ output matrix C are:

$$L^*_{ij} = L_{ij} - S_{ij} = \frac{\partial \psi_i^{(c)}}{\partial x_j} + \frac{\partial \psi_i^{(p)}}{\partial x_j},$$

$$C_j = \frac{\partial z_p}{\partial x_j}, \tag{2}$$

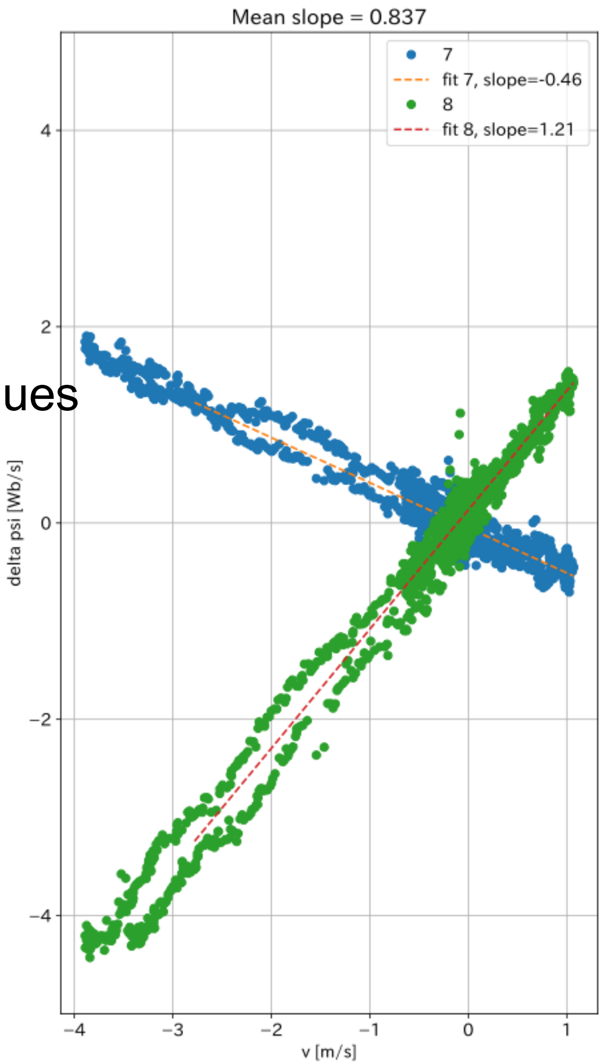
↑

Computed from equilibrium changes due to coil variations

[1] A. Portone, “The stability margin of elongated plasmas,” Nucl. Fusion **45**(8), 926–932 (2005).

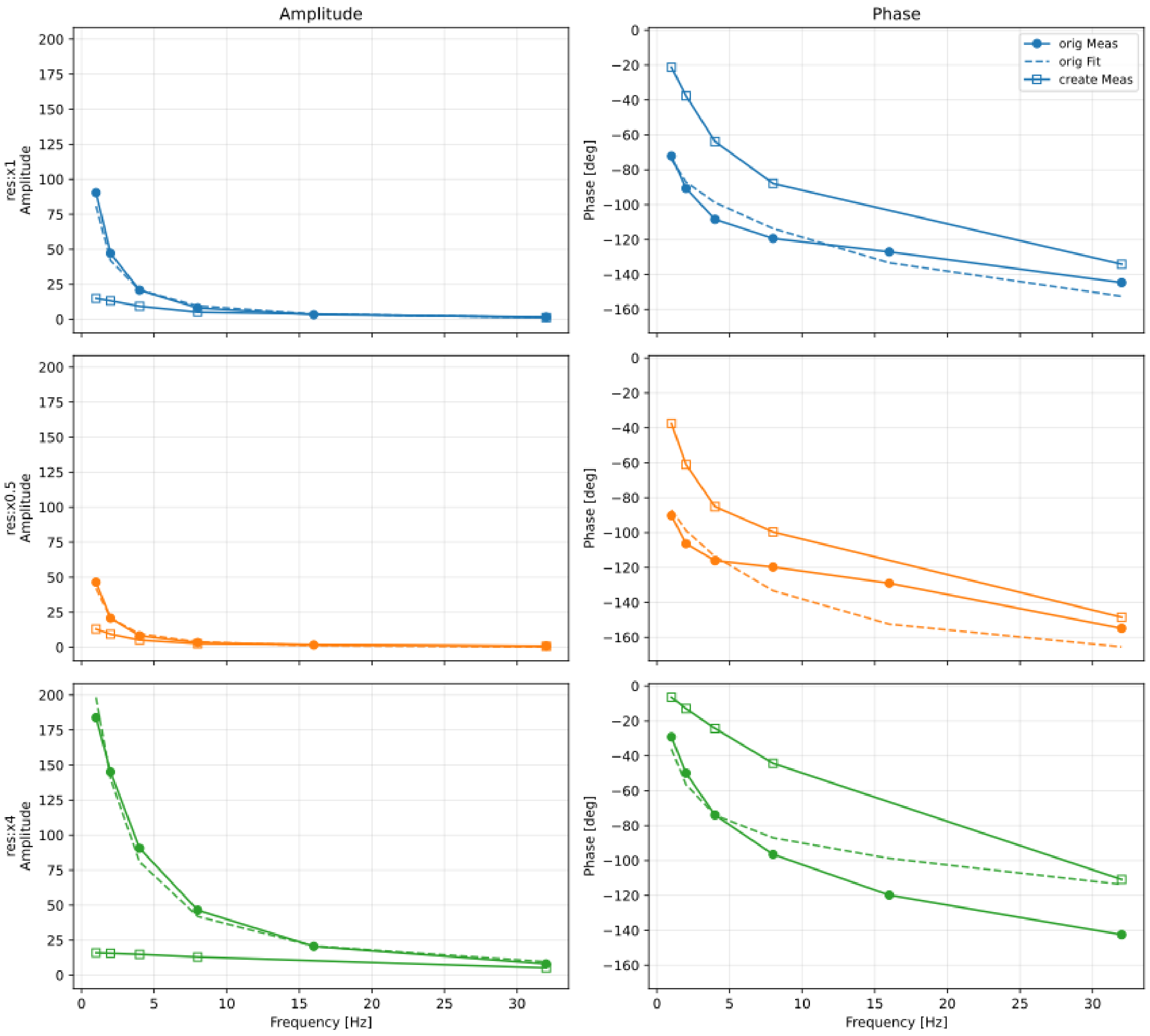
Stabilization effect of controller (preliminary)

Control values
Ref 7 & 8



- $\Delta\Psi = \Psi_X - \Psi_i$ (magnetic flux for control)
- Derivative control value: $\frac{d}{dt}\Delta\Psi = \frac{\delta(\Psi_X - \Psi_i)}{\delta t} \simeq \frac{d\psi}{dt} \equiv X$, where ψ is a perturbed magnetic flux
- $\tau_W \dot{\psi} - \gamma_0 \tau_W \psi = G\psi \rightarrow \tau_W \dot{X} - \gamma_0 \tau_W X = GX$
- Controller compensate $G_\mathrm{d} \frac{\delta(\Psi_X - \Psi_i)}{\delta t}$ for 250 us
- If GX is constant during δt =250 us, from $\int_0^{\delta t} GXdt = G_\mathrm{d} \frac{\delta(\Psi_X - \Psi_i)}{\delta t}$
  $$G = G_d/\delta t = 10^{-4} \times 4000 = 0.4$$
- From the figure X corresponds to the vertical velocity, thus G can be compared to γ of vertical instability,
  $$G = 0.4 \ll \gamma_0 \sim 50$$
- $\dot{X} \sim v$
- Experimentally applied gains and observed growth rate strongly indicates that the controller has the stabilization effect against vertical instability

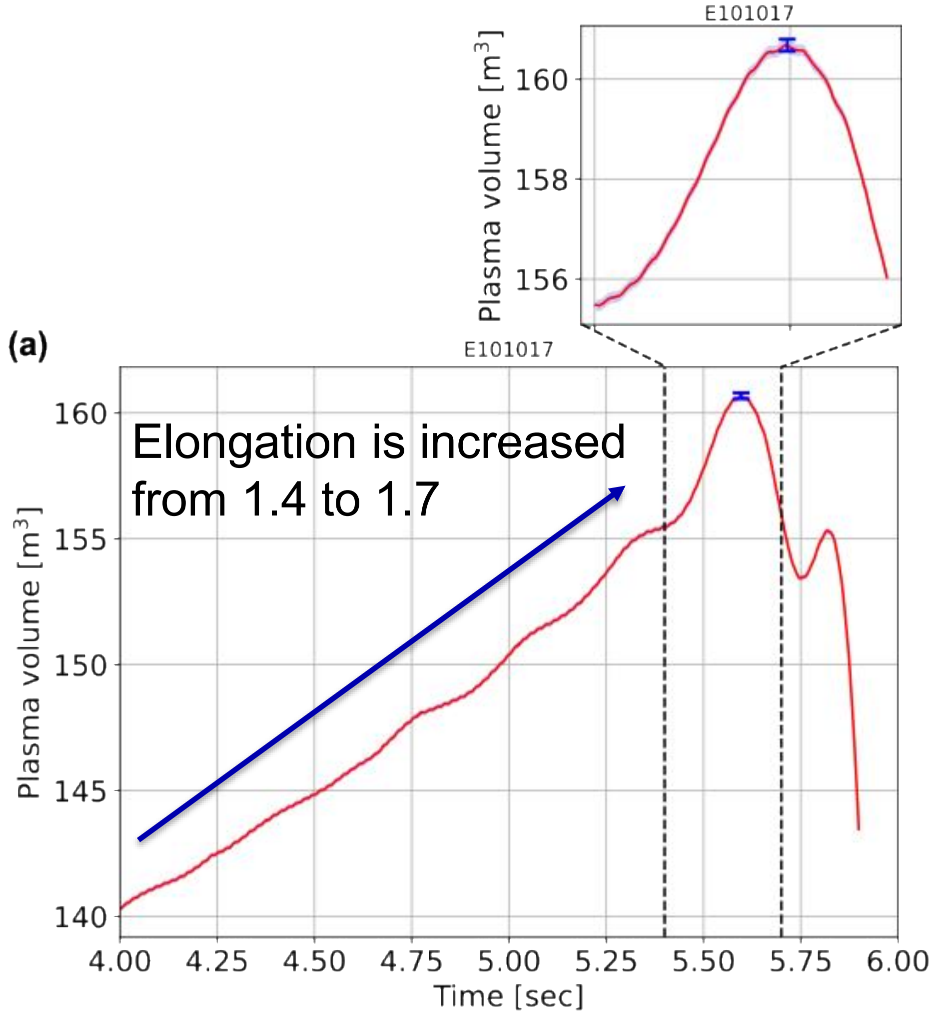
with phase

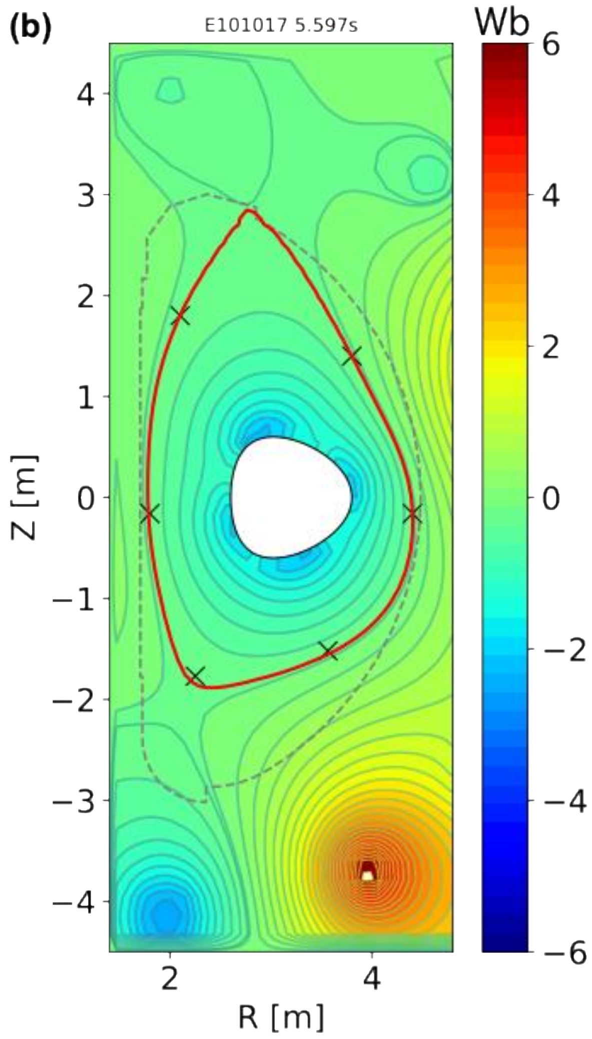


Amplitude
Phase
orig Meas
orig Fit
create Meas
res:x1
Amplitude
res:x0.5
Amplitude
res:x4
Amplitude
Phase [deg]
Frequency [Hz]

Largest Plasma Volume 160 m^3 was achieved by increasing elongation

Errors are quite small < 1% => small drifts & noises





Guinness Certificate